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# SEARCHING FOR NEW W's AND ASSOCIATED NEUTRINOS

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Summary

Several alternative scenarios for new W's and their associated neutrinos are explored with emphasis on the discovery of these particles at ep and pp colliders.

New massive gauge particles, beyond the $\gamma$, W and Z of the Glashow-Weinberg-Salam (GWS) model, are required in extended models of the electroweak interactions. Often they are accompanied by new, possibly heavy, neutral leptons. A particularly attractive class of models is those with asymptotic left-right symmetry, e.g. $SU(2)_L \times SU(2)_R \times U(1)$, in which three new gauge particles appear -- $W_R^\pm$ and Z' -- as well as new neutral leptons $N_e$, $N_\mu$, $N_\tau$ which couple primarily to the $W_R^\pm$ as opposed to the GWS $W_L^\pm$.[1] While there are no iron-clad limits, the simpler and more elegant L/R symmetric models have approximately equal couplings $g_L$ and $g_R$ for $W_L \to e\,\nu_e$ and $W_R \to e\,N_e$, respectively. In this case consideration of the $W_R$ contribution to $m(K_L) - m(K_S)$ leads to the bound $m(W_R) \geq 1.6$ TeV.[2] More elaborate calculations or models can tolerate $m(W_R)$ as low as 0.8 TeV.[3]

There are a variety of possibilities for the N's accompanying a new $W_R$. These include:[4]

a) The $N_e$ is the right-handed Dirac partner of $\nu_e$, or it is another light neutrino which does not mix with $\nu_e$.

b) The $N_e$ mixes with $\nu_e$ via a simple mass matrix of the form

$$\begin{pmatrix} 0 & m(e) \\ m(e) & m(N_e) \end{pmatrix},$$

with $m(N_e) \gg m(e)$ assumed. Then $m(N_e) \approx m^2(e)/\bar{m}(\nu_e) > 5$ GeV, since $m(\nu_e) < 50$ eV. Correspondingly, there is an $N_e\, e\, W_L$ coupling, but it is weaker than the $\nu_e\, e\, W_L$ coupling by the mixing matrix element $U \approx m(\nu_e)/m(e) < 10^{-4}$. The $N_e$ is a Majorana particle.

c) The $N_e$ mixes with $\nu_e$ in another manner which does not constrain U to such small values. (The only model-independent bound is $U < 0.2$.) In such models $\nu_e$ can be massless and $N_e$ can be a Dirac particle.[5]

L/R symmetric models tend to be of class b). In this note we will not consider very massive N, $m(N) > m(W_L)$, $m(W_R)$. Both production rates and decay modes would be considerably altered from those given here in that case.

Obviously the possibilities a)-c) lead to large uncertainties in the phenomenology of $W_R$ and N production and decay. In case a) N may be stable and can only be produced in processes involving the $W_R^\pm$. In cases b) and c) N will decay. If $W_R$ exchange (as opposed to mixing) dominates N decay, the lifetime (assuming $m(N) < m(t)$) is

$$\tau_N = 2.5 \times 10^{-10} \left(\frac{5\ \text{GeV}}{m(N)}\right)^5 \left(\frac{m(W_R)}{1.6\ \text{TeV}}\right)^4 \text{sec.} \qquad (1)$$

Thus, for $m(W_R) = 1.6$ TeV and $E_N$ of order 1 TeV, the N travels 15 m before decay (thus escaping from any detector) if $m(N) = 5$ GeV. However, it only travels 25 cm before decay if $m(N) = 10$ GeV. Note that the amplitudes for decay via mixing (i.e., via the $N_e\, e\, W_L$ coupling) and via $W_R$ exchange, $A_{mix}$ (decay) and $A_{W_R}$ (decay), are in the ratio

$$\frac{A_{mix}(\text{decay})}{A_{W_R}(\text{decay})} \approx U\, \frac{m^2(W_R)}{m^2(W_L)} \quad . \qquad (2)$$

Hence, in case b) $W_R$ exchange may very well be the dominant decay mechanism, given the bounds that we have quoted. However, in case c), where U could be $10^{-3} - 10^{-1}$, mixing may dominate. Then[4]

$$\tau_N \approx 1 \times 10^{-15} \left(\frac{5\ \text{GeV}}{m(N)}\right)^{5.2} \frac{1}{|U|^2}\ \text{sec}\ , \qquad (3)$$

a possibly shorter lifetime than in the $W_R$-dominated case.

The decay modes for a Majorana N depend upon whether the mixing or $W_R$ mechanism dominates. For heavy enough $N_e$ (but $m(N_e) < m(t)$, $m(N_\mu)$, $m(N_\tau)$) we have roughly:[5]

| | | Branching Ratio |
|---|---|---|
| $N \xrightarrow{W_R}$ | $e^- + 2$ jets | .50 |
| | $e^+ + 2$ jets | .50 |
| or | | |
| $N \xrightarrow{\text{Mixing}}$ | $e^- + 2$ jets | .24 |
| | $e^+ + 2$ jets | .24 |
| | $\overset{(-)}{\nu}_e + 2$ jets | .19 |
| | $\overset{(-)}{\nu}_e + \ell^+ + \ell^-$; $\ell = e, \mu, \tau$ | .11 |
| | $\overset{(-)}{\nu}_\mu + e^\pm + \mu^\mp$ and $\overset{(-)}{\nu}_\tau + e^\pm + \tau^\mp$ | .16 |
| | $\overset{(-)}{\nu}_e\, \nu_\ell \bar{\nu}_\ell$; $\ell = e, \mu, \tau$ | .06 |

It follows from CP invariance that the Majorana N will decay as often to an $e^+$ as to an $e^-$. This fact, reflected in the above table, gives the decays of this particle a very distinctive signature. Note also that the dominant decay channels are fully reconstructable.

We now turn to experimental possibilities for discovering such a $W_R$ and/or N. We consider both ep and pp collisions. In ep collisions the $W_R$ is not directly produced but, rather, appears as a virtually exchanged particle in the charged current reaction ep → $N_e$ X. The $N_e$ may or may not decay (detectably) in the detector. In pp collisions the $W_R$ can be produced approximately on shell or probed virtually, off its pole. Both contributions yield an $e^- \overset{(-)}{N}_e$ (or $e^+ N_e$) final state where again the $N_e$ may or may not decay.

In estimating cross sections we will assume $g_L = g_R$. In discussing detectability we will assume a standard operating year with an intergrated luminosity of $10^{40}/cm^2$. We consider two beam energies, 30 GeV and 140 GeV, for the electron beam,[6] and employ 20 TeV for the proton beam(s) (i.e. $\sqrt{s}$ = 40 TeV for the pp collider). We assume that the 30 GeV $e^-$ beam can be 80% polarized, but that the 140 GeV beam is not polarizable. Absolute discovery limits for $W_R$ may be inferred from Figs. 1a and 1b in the ep and pp cases.[7]

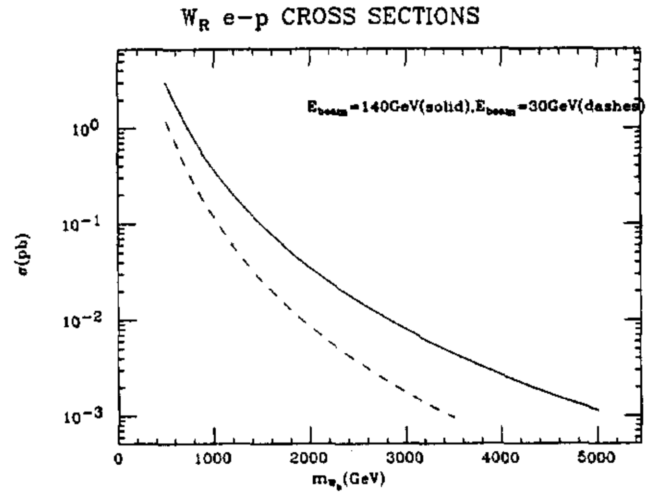


FIG. 1a. Cross sections for charged current reactions due to $W_R$ exchange as a function of m($W_R$) for $e^-$-beam energies of 140 GeV and 30 GeV. No $Q^2$ cut is imposed.

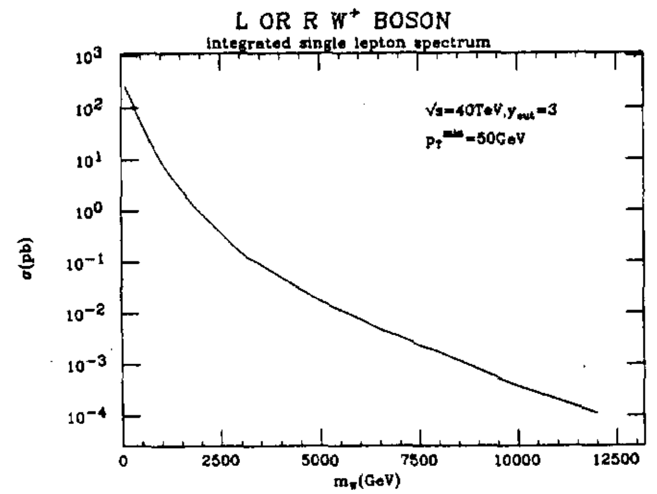


*FIG. 1b. The integrated cross section for* pp → $W^+_{L\ or\ R}$ + X → $e^+$ "N" + X (m(N) light compared to 50 GeV) for $e^+$ and N rapidities in the interval $-3 < y < 3$ and for $p_T$ of the $e^+$ > 50 GeV.

On the basis of ≈20 events per year a 30 GeV ep machine can reach m($W_R$) ≈ 2.8 TeV, a 140 GeV ep machine m($W_R$) ≈ 4.2 TeV, and a pp machine m($W_R$) ≈ 8 TeV. Whether these discovery limits, based on raw event rates, are realistic depends upon additional details as discussed below.

Consider first the N scenario a) or any other for which N does not decay in the apparatus. In ep *collisions the only signal for the presence of* $W_R$ is then an enhancement of the charged current cross section over that expected on the basis of $W_L$ exchange alone. The latter cross section is, or course, much larger. However, the $W_R$ and $W_L$ exchange amplitudes are in the ratio

$$\frac{A_{W_R}}{A_{W_L}} \approx \frac{Q^2 + m^2(W_L)}{Q^2 + m^2(W_R)} , \qquad (4)$$

so a $Q^2$ cut, $Q^2 > Q^2_{min} \approx m^2(W_R)$, will make the $W_R$ signal detectable. (Here $Q^2$ is measured via the current jet. Note that a $Q^2$ cut also helps to eliminate accidental backgrounds from γ-and Z-exchange neutral current events.) Given systematic uncertainties due to theoretical and experimental sources (especially quark distribution functions) we *estimate that a ≈25% effect is necessary to achieve a* reliable $W_R$ signal. Fig. 2 (plotted for m($W_R$) = 1.6 TeV) indicates that $Q^2_{min} \approx m^2(W_R)$ achieves this requirement at $E_{beam}$ = 140 GeV with a ratio

$$\frac{R + L}{L} \approx \frac{\#\text{ evts. } (W_L + W_R)}{\#\text{ evts. } (W_L \text{ only})} \approx \frac{65}{50} . \qquad (5)$$

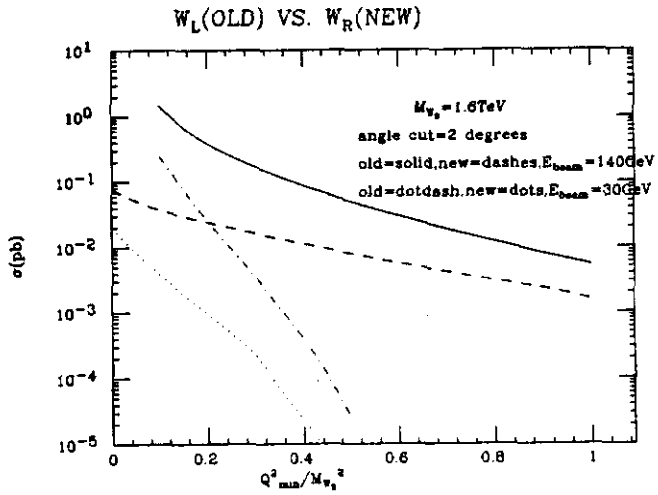


*FIG. 2. Cross sections for charged current reactions* due to new $W_R$ exchange compared to old $W_L$ (83 GeV) exchange for m($W_R$) = 1.6 TeV as a function of $Q^2_{min}/m^2(W_R)$ at e-beam energies of 140 GeV and 30 GeV. All $Q^2$ values > $Q^2_{min}$ are integrated over.

Since such statistics are already very marginal, higher m($W_R$) values are not achievable. Figure 2 shows that for $E_{beam}$ = 30 GeV such a restrictive $Q^2$ cut is not possible. In order to have a measurable raw event rate for the $W_R$ signal $Q^2_{min} \approx 0.1\ m^2(W_R)$ is appropriate. However, the $W_L$ background now exceeds the $W_R$ signal by nearly a factor of 100. The only hope in this case is to employ electron beam polarization. With 80% right-handed polarization, and at the same $Q^2_{min}$ and m($W_R$) values,

$$\frac{R + L}{L} = \frac{572}{500}\ ; \qquad (6)$$

i.e., one achieves a $3\sigma$ effect. Thus $m(W_R) = 1.6$ TeV is at the limit of detectability with either electron beam. A similar analysis for $m(W_R) = 1$ TeV indicates that such a $W_R$ is detectable without difficulty. In pp collisions the discovery of $W_R$ (decaying to an unobservable N plus charged lepton) relies on the same technique as employed at the CERN Sp$\bar{p}$S in discovering the $W_L$ (83 GeV). Backgrounds are expected to be small and systematics of quark distribution functions, etc., are not significant. Figure 3 illustrates the single lepton spectrum $d\sigma/dydp_T$ as a function of $p_T$ at $y = 0$ for an 8 TeV and a 10 TeV $W_R^+$ in comparison to backgrounds from old physics (Drell-Yan $\gamma \to e^+e^-$ and $W_L^+ \to e^+\nu_e$).

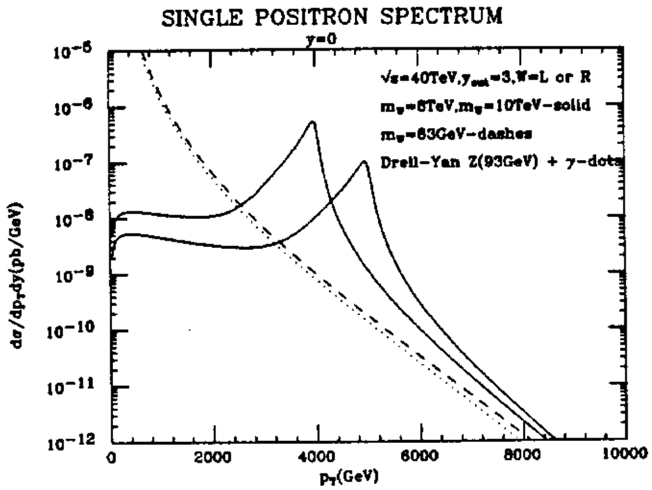


FIG. 3. The single lepton spectrum for $pp \to W_{L\ or\ R}^+ X \to e^+ X$ for $m(W) = 8$ and 10 TeV compared to backgrounds from Drell-Yan $pp \to \gamma X \to e^+ X$ and $pp \to W_L^+$ (83 GeV) $X \to e^+ X$. The rapidity of the $e^+$ is zero and the balancing $\nu_e$ is constrained to be "missing" in the rapidity interval $-3 < y(\nu_e) < 3$.

We have imposed an apparatus cut ($|y| \leq 3$) on the opposing lepton so that the D-Y background can be eliminated. The $W_R$ Jacobian peak is clearly observable but the integrated event rate under the peak but above the background is only two events per year in the 10 TeV case. Thus $m(W_R) = 10$ TeV is marginal at a pp collider in the same sense that $m(W_R) = 1.6$ TeV is marginal at the ep machines. However, since these few events will be clean, the nominal 8 TeV discovery limit quoted earlier, for which there are 11 events under the peak, can perhaps be extended to near 10 TeV.

In cases where the N decays (either by mixing or $W_R$ mediation) in the detector, a much more distinctive signature will be apparent in the ep experiments. Normal charged current events will no longer be a background. For a Majorana N there will be frequent processes of the type $e^- p \to e^+ X$, where the wrong sign lepton $e^+$ will be accompanied by hadronic jets. Furthermore, the $Q^2$ computed from the $e^-$ and $e^+$ momenta will disagree significantly with the true $Q^2$ carried by the exchanged $W_R$. The true $Q^2$ may be calculated using the momentum of the "current" jet from the hadron vertex, which on average will be in a different kinematical region from the hadronic jets associated with the $e^+$.[8] Adding the latter jets to the $e^+$ (i.e., reconstructing the N momentum) should produce consistency between the two different $Q^2$ calculations. Majorana or not, N decays will always lead to $e^- p \to e^- X$ events exhibiting the same $Q^2$ peculiarities. In the Majorana case, these events occur at the same rate as the $e^+$ events. Backgrounds to these signatures can come from two sources:

a) Radiative corrections to normal neutral current events. One requires more powers of $\alpha$ for $e^- p \to e^+ X$ than for $e^- p \to e^- X$ so that these rates should differ considerably. The magnitude of such backgrounds has not been computed but we will assume it to be small.

b) Mixing production. Here we imagine a moderate value for U, in which case $e^- p \to N_e X$ can occur via $N_e - \nu_e$ mixing and $W_L$ exchange. If discovery of a new $W_R$ is the goal, this process is a background. The relative amplitudes are

$$A_{mix}(e \to N) = \frac{U}{Q^2 + m^2(W_L)}$$

and $\qquad (7)$

$$A_{W_R}(e \to N) = \frac{1}{Q^2 + m^2(W_R)}\ .$$

A $Q^2$ cut will help to reduce the background from $A_{mix}$. Probably $Q^2 > 0.1\ m^2(W_R)$ will eliminate it for any reasonable value of U. For the 30 GeV e beam and $m(W_R) = 2$ TeV, such a cut leaves $\approx 10$ events in a standard year. If U is negligible the cut is not required and the event rates computed from Fig. 1a are appropriate ($\approx 80$ evts at $m(W_R) = 2$ TeV and $\approx 30$ at $m(W_R) = 2.5$ TeV at $E_{beam} = 30$). For the 140 GeV e beam energy we can obviously reach higher $m(W_R)$ values, up to $m(W_R) = 4$ TeV if no $Q^2$ cut is required.

In pp collisions the decay of the N is not obviously beneficial or harmful to the signature for $W_R$ production. It is still difficult to imagine backgrounds that could produce a single highly energetic electron in one hemisphere of a detector and a balancing reconstructable $e^-$ or $e^+$ + 2 jet signal in the other hemisphere. The Jacobian peak will still be present and clean. In particular the Jacobian peak region would have only a very small background from $W_L^{off-shell}$ (83 GeV) $\to e\ \underrightarrow{N}_{decay}$. See Fig. 3 to see how small even the normal $e^-\nu_e$ background is in the Jacobian peak region. Thus the 8 TeV nominal limit may again be too conservative and a few clean events could reveal $W_R$ production up to $m(W_R) \lesssim 10$ TeV. Note that at $m(W_R) = 4$ TeV, the upper limit for ep machines under discussion, we have

$$\frac{\#\ \text{events (ep at 140 GeV + 20 TeV)}}{\#\ \text{events (pp at}\ \sqrt{s} = 40\ \text{TeV)}} = \frac{1}{20}\ . \qquad (8)$$

Once a new W is discovered, can one determine whether it is a $W_R$ or a new $W_L'$? (There is no compelling reason to suppose that a $W_L'$ would be associated with a new N, or, if it is, that this N would be heavy. Thus, $W_L'$ phenomenology will most likely correspond to the non-decaying N discussion given earlier.) For W's accessible in 30 GeV × 20 TeV ep collisions, the option of polarizing the e beam makes it easy to distinguish a $W_L'$ from a $W_R$. Using the wrong polarization simply removes the signal. In the absence of beam polarization, $W_{R/L}$, differentiation is impossible in ep collisions unless the N decays in the detector. If it does decay, this differentiation is still next-to-impossible if the new W dominates both the production and decay of the N. Changing this W from a $W_R$ to a $W_L'$ reverses the helicity of both the N and its daughter $e^-$ (or $e^+$). Hence, the correlation between these two helicities, which influences the angular distribution of the daughter $e^-$ in the N rest frame, does not change. Indeed, one can show that the $e^-$ angular distributions are identical in the two cases. Observing additional N decay fragments would not help, except for exotic final states. However, suppose one imposes a $Q^2$ cut so that $W_{R/L'}$ exchange, and not old $W_L$ exchange with $N-\nu_e$ mixing, dominates N production, but U is large enough so that the latter mechanism dominates the decay. Then the angular distribution of the daughter $e^-$ (or $e^+$) will reveal the handedness of the $W_{R/L'}$. The presence of mixing-induced decays can be established through the observation of decay modes such as $\nu$ + 2 hadron jets which do not result from $W_R$-mediated decays (see table).

In pp collisions the handedness of the produced $W_{R/L'}$ can be determined using $W \to \tau$ decay modes. This procedure is discussed in a separate contribution to these Proceedings. It requires high statistics and restricts the range of $m(W_{R/L'})$ for which the technique can be employed.

Finally, if $m(W_R)$ is very large we may still be able to see the N, either in ep or pp collisions, if there is $N - \nu_e$ mixing. The Majorana N decay signatures are sufficiently distinctive that perhaps U's as small as $10^{-2}$ (relative production rates compared to $\nu$ of order $10^{-4}$) could be detectable in a high statistics experiment.

## Acknowledgments

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## References and Footnotes

1. For a recent review, see R. Mohapatra, University of Maryland preprint based on lectures delivered at the Nato Summer School on Particle Physics, Munich, 1983. For early work on the phenomenology of a $W_R^\pm$, see M.A.B. Beg, R. Budny, R. Mohapatra, and A. Sirlin, Phys. Rev. Lett. 38, 1252 (1977).

2. G. Beall, M. Bander, and A. Soni, Phys. Rev. Lett. 48, 848 (1982).

3. Private communications from N. Deshpande, F. Gilman, and R. Mohapatra.

4. M. Gronau, C.N. Leung, and J.L. Rosner, Phys. Rev. D29, 2539 (1984). See also P. Langacker, R.W. Robinett, and J.L. Rosner, Enrico Fermi Institute preprint EFI 84/12.

5. If one combines appropriate decay modes in the following table, the branching ratios agree with those in Gronau et al., Ref. 4, which were computed assuming N is a Dirac particle.

6. These are the two beam energies considered by the ep working group at this Workshop.

7. The ep calculations were done using modified versions of the programs of J. Bagger and M. Peskin. (See C. Prescott, in PSSC Summary Report (Fermilab, June, 1984), p. 68.) For the pp calculations see also J.F. Gunion, these Proceedings.

8. Calculations of lepton and current jet kinematics were performed by M. Shaevitz at this Workshop. See also C. Prescott, Ref. 7.